would allow. The flow of air was then so large that the cylinder of gauze M produced too much choking to give a convenient reading of the oil-gauge, and it had to be removed, so that the choking was then supplied by the tube connecting E and N (fig. 2) and a very small piece of cotton-wool in N. Even under these conditions the readings of the oil-gauge were fairly steady with this nozzle. The first reading of p_1 was of course not very low in this case, but it is seen to lie well on the horizontal portion of the curve. The result for the nozzle of larger diameter is seen to be practically the same as that for a smaller one of the same shape.

In conclusion I wish to thank Prof. the Hon. R. J. Strutt, F.R.S., for advice on many points, and for the keen interest he has taken in the work throughout its progress.

On the Relation between Barometric Pressure and the Water-level in a Well at Kew Observatory, Richmond.

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I. *Introductory.*

The investigation which forms the subject of the present communication must be regarded as forming part of a general inquiry into the mode of action of the well at Kew Observatory, Richmond. The well was sunk during the course of some extensive alterations to the building about four years ago, and the water-level has been continuously recorded since the end of July, 1914. The mean level for each day expressed in centimetres above Ordnance Datum has been published in the 'Geophysical Journal,' and the extreme values for each month have usually been given in the Monthly Weather Report. After being in action for two years, it was thought desirable to undertake a somewhat detailed examination of the records which had accumulated. The most interesting feature of the inquiry proved to be the periodic variations of level, which were to be attributed to the tidal oscillations of the neighbouring River Thames. The most noteworthy response of the well was found in the case of the lunar fortnightly oscillation, which could, indeed, be plainly seen by merely plotting successive daily mean levels on a fairly open scale.

The solar and lunar diurnal, semi-diurnal, ter-diurnal, ..., oscillations were sought for by forming solar and lunar diurnal inequalities at two-hour intervals and analysing the resultant variations. During the course of this work, it soon became evident that the extent of the solar diurnal variation was very much greater than one had any right to expect, and one inferred that the solar tides were not alone concerned in its production. The effect of barometric pressure suggested itself as a likely factor, and an investigation was accordingly taken in hand.

Full details of the method of registration and of standardising the traces, as well as a description of the site of the well, will appear in the paper embodying the results of the work on the tidal phenomena. Some of the results are quoted in this paper where necessary. With these exceptions, the inquiry relating to the effect of barometric pressure forms a more or less complete study in itself, and, from this point of view, the results would seem to be of sufficient interest to justify their being brought before the Society.

The well referred to penetrates to a depth of 11 feet below the basement of the Observatory, the bottom being 150 cm. above Ordnance Datum. The soil consists of sand and coarse gravel resting upon London Clay, at a depth of about 9 or 10 feet. The well is about 300 yards from the Thames.

II. *The Relation between Changes of Pressure and Water-level.*

The direct detection of a relation between atmospheric pressure and water-level is a matter of no little difficulty, on account of the multiplicity of factors which have been found to control the latter. Beside the regular tidal effects, the well shows the usual type of seasonal variation, with a maximum late in winter and a minimum in the late autumn. During the winter the changes of level may be very rapid and irregular, particularly at times of flood. The well also appears to be highly sensitive to rainfall. Any connection between the height of the barometer and the height of the water in the well is therefore almost certain to be masked in a short series of observations by the large deviations due to those causes. After consideration, the following method was adopted: The change of level between 4 h. and 7 h. G.M.T. each day was measured on the trace in millimetres. The figure given in the Daily Weather Report for the barometric change in three hours ending at 7 h. was then written down in an adjacent column. This was done for each day of the two years, August, 1914, to July, 1916, with only such omissions as were necessitated by loss of record. For brevity, the changes of level and of pressure during the three hours ending at 7 h. will be denoted by δU and δP respectively; δu and δp will denote corresponding small changes of level and pressure in general.

In the Daily Weather Report the value of δP takes the form of an integer—the unit being the half-millibar—to which a positive or negative sign is prefixed, to indicate a rising or falling barometer.* The same convention was adopted in tabulating the value of δU. On account of the diurnal variation of pressure, the mean value of δP is about +0·3 mb., but the passage of depressions and anticyclones introduces sufficient variation to produce a fairly normal distribution, in which values up to ±4·5 mb. occur with sufficient frequency. Retaining the unit of the half-millibar, we may, then, place a given value of δU in one of 19 classes, according as the value of δP given in the Daily Weather Report is $-9, -8, \ldots, 0, \ldots, +8$, or $+9$. A few values of δP of higher magnitude occurred during the period under examination, but they have not been employed in the subsequent work. The mean value of δU for each class, together with the frequency, for the whole period, is given in Table I.

Table I.

δP (unit 0·5 mb.) ……	−9	−8	−7	−6	−5	−4	−3	−2	−1	0
δU in millimetres ……	+2·00	+4·75	+9·40	+3·43	+1·80	+2·00	+0·46	+0·56	−0·43	−1·20
No. of observations ……	2	4	2	8	5	21	31	33	56	122

										Mean.
δP (unit 0·5 mb.) ……	+1	+2	+3	+4	+5	+6	+7	+8	+9	+0·720
δU in millimetres ……	−1·24	−2·05	−1·94	−1·93	−0·81	−3·75	−3·71	−0·80	−14·25	−1·09
No. of observations ……	126	125	66	31	14	11	7	2	2	668

There are some irregularities, but the tendency for negative values of δP to be associated with positive departures from the mean value of δU is manifest. The values of δP and δU in the Table give a correlation coefficient of −0·88, which is high enough to place the reality of the connection beyond reasonable question. The corresponding regression equation is

$$\delta u = -0{\cdot}533\,\delta p$$

or, converting the pressure units to millibars,

$$\delta u = -1{\cdot}07\,\delta p,$$

whence it appears that on the average an increase of pressure of 1 mb., spread over a period of three hours, is accompanied by a depression of the water-level amounting to rather more than a millimetre.

The preliminary work having been successful, in so far as it indicated a definite connection between changes of pressure and water-level, it was thought desirable to extend the inquiry with the object of determining:

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* More accurately, a negative sign indicates that the barometer was higher at 4 h. than at 7 h., and *vice versâ*.

(1) Whether the value of the ratio $\delta u/\delta p$ depended upon the sign of δp, or upon the value of dp/dt; in other words, whether the relation between δU and δP were linear.

(2) Whether the value of $\delta u/\delta p$ were subject to seasonal variation,

(3) Whether there were any lag in the response of the water-level to changes of pressure.

III. *Form of the Relation between δu and δp.*

The figures given in Table I are too irregular to permit of any conclusions being drawn regarding the linearity or otherwise of the relation between δu and δp. In order to obtain a smoother curve the fifteen classes included between $\delta P = -7$ and $\delta P = +7$ were reduced to five by combining successive groups of three. The results obtained in this way are given in Table II.

Table II.

<table>
<tr><td>Mean δP ....</td><td colspan="2">−5·80</td><td colspan="2">−2·86</td><td colspan="2">+0·23</td><td colspan="2">+2·58</td><td colspan="2">+5·78</td></tr>
<tr><td>Mean δU ....</td><td colspan="2">+3·69</td><td colspan="2">+0·88</td><td colspan="2">−1·07</td><td colspan="2">−2·00</td><td colspan="2">−2·46</td></tr>
<tr><td>δu/δp (in mm./mb.)......</td><td></td><td colspan="2">−1·91</td><td colspan="2">−1·26</td><td colspan="2">−0·79</td><td colspan="2">−0·29</td><td></td></tr>
</table>

Plotting δU against δP (fig. 1) it is seen that the slope of the curve decreases uniformly in going from negative to positive values of δP. Before accepting this conclusion as representing a genuine phenomenon there are certain points to be considered. In the first place, the observations are not really homogeneous. The more rapid changes of barometric pressure are almost entirely confined to the winter months. Consequently, values of δP of ±4 and upwards are very much more frequent during the winter than

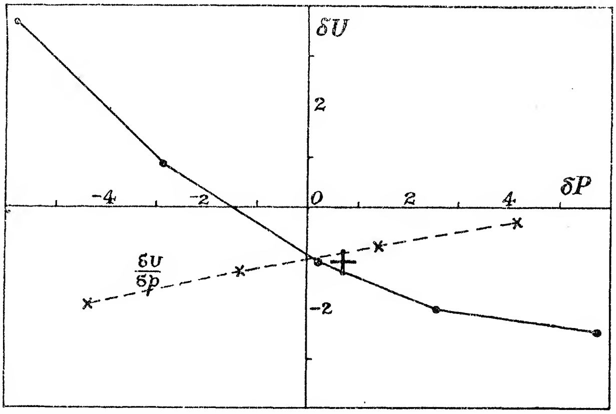

Fig. 1.—The mean values of δU and δP are shown by the large cross.

during the rest of the year. We cannot, therefore, regard the first and last entries in Table II as fairly representing general conditions throughout the year. Again, it will be observed that the curve does not pass through the point representing the mean values of the two quantities. This means that a small depression of water-level occurs without change of pressure, which seems to indicate that "accidental" features have not been completely eliminated.

For the purpose of investigating the existence of a seasonal variation of $\delta u/\delta p$ the data were subdivided into three groups in a manner to be explained presently. From what has been said above, it appears essential to treat the data according to a seasonal classification before further progress can be made towards interpreting the results so far obtained. I will therefore proceed at once to the consideration of our second object of inquiry, the results of which may be expected to throw some light on the question as to whether the relation between δu and δp is really linear or not.

IV. *Seasonal Variation.*

It has been previously remarked that the water-level at Kew shows a pronounced seasonal variation, the highest levels normally occurring in winter, followed by a steady drop to a minimum late in the autumn. In the work on the tidal phenomena it was found that the sensitiveness of the water-level to all kinds of variation was intimately related to the height of the water. For example, the ranges of the solar and lunar diurnal variations obtained from monthly mean inequalities were both found to increase with rise of the mean level, the correlation coefficients being about +·9 in each case. It was therefore thought best to take the water-level as a basis of classification rather than to employ the ordinary seasonal subdivisions of the year. The following three groups of months were formed:—

Group I.—High-Level Months.

1915	January	(381)
1915	February	(370)
1915	March	(331)
1915	December	(355)
1916	January	(352)
1916	February	(330)
1916	March	(400)
1916	April	(364)

Mean level = 360 cm. above M.S.L.
= 190 cm. below ground level.

Group II.—Intermediate Months.

1915	April	(273)
1915	May	(252)
1916	May	(286)
1916	June	(245)

Mean level = 264 cm. above M.S.L.
= 286 cm. below ground level.

Group III.—Low-level Months.

1914	August	(191)
1914	September	(183)
1914	October	(176)
1914	November	(175)
1914	December	(237)
1915	June	(237)
1915	July	(214)
1915	August	(217)
1915	September	(205)
1915	October	(208)
1915	November	(225)
1916	July	(223)

Mean level = 208 cm. above M.S.L.
= 342 cm. below ground level.

The figures in parenthesis give the mean heights of the water in centimetres above mean sea level. The above classification, although quite arbitrary, was found to be very satisfactory in practice. There were many advantages and apparently no serious objections attending the use of the same groups in the present work, and they were accordingly adopted.

The method followed has been similar to that used in Table II, with the exception that only three classes have been retained, comprising values of δP: -4, -3, -2; -1, 0, $+1$; $+2$, $+3$ and $+4$. The observations in each class are usually sufficiently numerous to give fairly reliable values, and the range of pressure is quite large enough, in view of the ultimate object of the inquiry, to determine what portion of the solar diurnal variation is to be attributed to the effect of barometric pressure.

In order to get some confirmation of the figures by comparing results obtained under similar but independent conditions the low-level and high-level months have each been considered in two groups. The complete results are given in Table III and shown graphically in fig. 2.

Table III.

Period.	Mean Level.	δP.			δU.			$\delta u/\delta p$.	$\delta u/\delta p$ (corrected).
	cm.	½ mb.	½ mb.	½ mb.	mm.	mm.	mm.	mm./mb.	mm./mb.
High-level months, 1915	359	−3·01	−0·10	+2·73	+2·46	−3·68	−2·01	−1·57	−1·63
High-level months, 1916	361	−2·91	+0·11	+2·57	+0·10	−2·89	−6·27	−2·31	−2·39
All high-level months ...	360	−3·00	+0·01	+2·65	+1·31	−3·24	−4·31	−2·01	−2·08
Intermediate months ...	264	−2·40	+0·23	+2·46	−0·55	−1·47	−2·78	−0·64	−0·66
Low-level months, 1914	192	−2·78	+0·42	+2·67	+0·89	+0·39	−0·27	−0·43	−0·44
Low-level months, 1915	218	−2·69	+0·24	+2·53	+0·49	−0·35	−0·80	−0·49	−0·51
All low-level months ...	208	−2·79	+0·31	+2·57	+0·67	−0·15	−0·65	−0·49	−0·51
Mean of all results	268	−2·86	+0·23	+2·58	+0·88	−1·07	−2·00	−1·07	−1·11

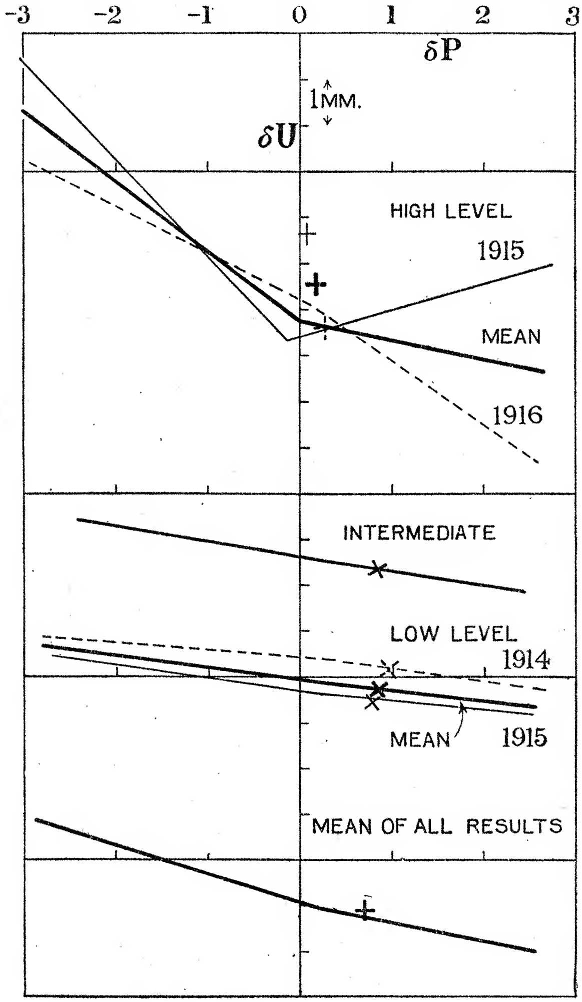

Fig. 2.—Mean values are shown by crosses.

It will be seen that with one noteworthy exception (high level, 1915) the three points lie fairly on a straight line passing through the point corresponding to the mean values. It seems fair to conclude that the exceptional character of the 1915 high-level curve must be entirely due to accidental circumstances. It must be remembered that changes of level are much more rapid and irregular during the high-level months than during other periods, and consequently a greater number of observations are necessary to reduce errors due to "accidental" movements (including in the latter term all movements which are not caused by changes of pressure) to a sufficient extent. It appears, then, that under similar conditions the effect of an increase of pressure of about 1·5 mb., spread over three hours, is equal and opposite to that produced by an equal decrease of pressure. Within those limits it would seem justifiable to generalise that conclusion. From three points only it is of course not possible to obtain the true course of the curve on which they lie, but we may fairly assume that a fourth point is given by the mean values of δU and δP. The results indicate that the four points lie on a straight line. We may therefore write in general

$$\delta u = a \,.\, \delta p,$$

at any rate so long as dp/dt does not exceed 0·5 mb. per hour. The factor a is always negative but varies with the amount of water in the well.

The values of the factor a, computed where necessary by the method of least squares, are given in the Table. The nature of the correction which has been applied in order to obtain the results in the last column will be explained in the following section. It will be seen that the sensitiveness of the water-level to changes of barometric pressure is conspicuously dependent upon the amount of water in the well, high levels being associated with high sensitiveness. This relation is similar to that observed in the case of lunar tides of short period and also in the case of rainfall. It appears, then, that the height of the water in the well may be regarded as an index of sensitiveness in general. The only exception which I have observed occurs in the case of the lunar fortnightly tides, the effect of which upon the well does not appear to vary much with the level.

Although it is convenient to state the general conclusion in the above form, there is good reason for believing that the connection is purely an indirect one, due to the fact that those conditions of the soil which are necessary for high sensitiveness occur only at times of high level. The condition of the soil, indeed, appears to be the chief if not the only factor which controls the sensitiveness. In the absence of accurate measurement a good idea of the sensitiveness is conveyed to the eye by the amount of incidental movement, or "embroidery" as it is usually termed, shown by the trace. Now when the water is rising rapidly from a low level to a higher one, which is frequently the case late in autumn, the appearance of the trace in all the cases I have examined is very different from that occurring during a fall of level through the same range. In the latter instance the sensitiveness appears to be much greater. I am unable to say whether the response to each factor is equally affected, but in the case of barometric pressure at any rate the sensitiveness characteristic of "high level" does not appear to manifest itself until the water has ceased rising for the time being. It is clear, then, that the sensitiveness is decided by the condition of the soil rather than by the absolute level. The difference between the high level results for 1915 and 1916 may, therefore, to some extent be real.

Reference may be made here to fig. 4, which represents the relation between level and sensitiveness so far as I have been able to ascertain it. I have made no attempt to represent the curve mathematically because the number of points is too small to define its exact shape with certainty. It would appear to be either hyperbolic or exponential in form. On the first supposition the sensitiveness is inversely proportional to the depth of the water-line below some fixed level. The extrapolation of the curve as it stands would result in the sensitiveness becoming infinite for a level of about 430 cm. or about 1·2 m. below the surface. This is, of course, out of the question, but there can hardly be any doubt that the value of $-\delta u/\delta p$ increases very rapidly as the water-level approaches the surface.

V. *Accuracy of the Results.*

For the purpose of ascertaining the main features of the phenomena under investigation, the data employed would seem to have been quite satisfactory. It will, however, ultimately be necessary to know the value of $\delta u/\delta p$ in the different groups with some accuracy. It is desirable therefore to form some idea of the probable errors involved.

Consider first the barometric data. The "barometric tendency" is determined at Kew by means of a Dines float barograph. The change of pressure in three hours is estimated with the help of horizontal lines, ruled by hand, whose distance apart is intended to represent 5 mb. of pressure (10 on the scale used in the Daily Weather Report). As the estimate has to be made while the chart is on the drum and under conditions of illumination which leave something to be desired, there is obviously scope for errors which may be important in the present connection. In order to form an idea of the accuracy obtained, I have compared the mean value of the barometric change from 4 h. to 7 h. in each month obtained from the "barometric tendency" (δP_1) with that obtained from the tabulated hourly values derived from the Kew photo-barograph (δP_2). The result of this comparison is given in Table IV.

Table IV.

Month.	δP_1 from D.W.R.	δP_2 from hourly values.	$\delta P_1 - \delta P_2$.	Month.	δP_1 from D.W.R.	δP_2 from hourly values.	$\delta P_1 - \delta P_2$.
1914.	mb.	mb.	mb.	1915.	mb.	mb.	mb.
August	0·403	0·381	0·022	August	0·580	0·464	0·116
September......	0·733	0·640	0·093	September......	0·416	0·380	0·036
October	0·548	0·319	0·229	October.........	0·242	0·203	0·039
November......	0·217	0·217	0	November......	0·350	0·384	−0·034
December	0·420	0·520	−0·100	December	−0·194	−0·226	0·032
1915.				1916.			
January	0·194	0·110	0·084	January	−0·016	−0·093	0·077
February	0·161	0·157	0·004	February	−0·017	−0·038	0·021
March	0·355	0·322	0·033	March	0·530	0·465	0·065
April	0·717	0·504	0·213	April	0·467	0·336	0·131
May	0·436	0·465	−0·029	May	0·323	0·358	−0·035
June	0·316	0·360	−0·044	June	0·350	0·293	0·057
July	0·532	0·555	−0·023	July	0·435	0·455	−0·020
Means	0·419	0·379	0·040	Means	0·289	0·249	0·040

For the two years the mean values are $\delta P_1 = 0{\cdot}354$ mb.; $\delta P_2 = 0{\cdot}314$ mb. We have now to decide whether this difference is due to some systematic error of observation. The root mean square value of $\delta P_1 - \delta P_2$ for individual months is 0·086 mb. If this is due to casual error the standard value of $\delta P_1 - \delta P_2$ for 24 months is $0{\cdot}086/\sqrt{24}$ or 0·0175 mb., and the probable error two-thirds of this, or 0·012 mb. The observed value (0·040) is more than three times this amount, which seems to suggest the probability of a systematic error in δP_1.

If we take 0·1 mb. as the standard error of an individual hourly reading of barometric pressure, the standard error of a monthly mean for a given hour is $0{\cdot}1/\sqrt{30}$ or 0·018 mb., and the standard error of δP_2 in a given month $0{\cdot}018 \times \sqrt{2}$ or 0·025 mb. The standard error of δP_1 is a good deal larger than this. The fact that the estimate is only made to the nearest half-millibar introduces a standard error of 0·25 mb. in an individual reading which would give rise to a standard error of 0·065 mb. in δP_2. The standard error of $\delta P_1 - \delta P_2$ is therefore $\sqrt{[(0{\cdot}025)^2 + (0{\cdot}065)^2]}$ or 0·070 mb. We have probably underestimated δP_1, since we have assumed that the estimate of the tendency is correct to the nearest half-millibar. The agreement with the observed value 0·086 mb. is therefore satisfactory.

One opportunity for the introduction of a systematic error immediately suggests itself, namely, the ruling of the charts. The accepted magnification-factor of the instrument is 2·10, with a probable error of about 1 per cent. The distance apart of the 5 mb. rulings should then be $2 \cdot 1 \times 5 \times 750/1000$ or 7·875 mm. The actual spacing was measured on two samples of 20 charts, selected at random from the curves for the year 1915. Both gave the same mean value, viz., 7·62 mm., the probable error being 0·03 mm. It appears then that the spacing was on the average 3·3 per cent. too narrow. If we make a correction on this account the mean value of δP_1 becomes 0·342, giving $\delta P_1 - \delta P_2 = 0 \cdot 028$ mb. If the same correction is applied to individual values of δP_1 it is found that the difference $\delta P_1 - \delta P_2$ is positive in 15 and negative in 9 cases out of the 24. There is no clear indication therefore that the remaining errors are anything but casual. A correction of $+3 \cdot 3$ per cent. has accordingly been applied to all the results in Table III.

From the foregoing discussion it might appear that it would have been desirable to use more precise barometric data—hourly tabulations for example. The relative uncertainty in the mean value of δU is, however, probably greater in general than that in δP, so that there was nothing to be gained by obtaining the latter quantity with all possible precision. The error in δU does not arise so much from errors of measurement as from fluctuations of water-level, due to causes other than changes of pressure, and is not easily estimated.

The best way of appraising the results is to compare values of $\delta u/\delta p$, obtained from different groups of months belonging to the same category. In the high-level class there is some discordance between the values for 1915 and 1916, although the mean levels were very nearly the same. It would appear that the uncertainty in the final value $-2 \cdot 08$ may amount to 20 per cent. or more.* The difference in the case of the two low-level groups is in the direction to be expected from the difference of level. The figure $-1 \cdot 11$ for the whole period rests upon about 600 observations. δP appears to be uncertain to the extent of about 8 per cent. over the whole period. The uncertainty in δU is probably of about the same order of magnitude, so that we can hardly suppose that the probable error is less than about 0·1 mm./mb.

VI. *Rapidity of Response to Pressure Changes.*

In the preceding sections we have compared the changes of water-level which occur simultaneously with given changes of pressure, and derived certain conclusions from the results. It is obvious, however, that those conclusions may be very largely in error unless it can be shown that the response of the well is not associated with lag.

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* This is the uncertainty involved in assigning a certain value of $\delta u/\delta p$ to the level of 360 cm. It necessarily includes the effect upon the average value of real differences of sensitiveness at the same level.

During high-level periods there is no difficulty in identifying movements of water-level which have taken place as the result of well-marked changes of barometric pressure. The passage of a depression, for example, is shown by a peak on the water-level trace. Two examples of such movements are shown in fig. 3. In the diagram the time scales of the barograph and water-level recorder have been brought into equality, and the barograph trace has been inverted. The former instrument actually records on a daily chart, and the latter on a weekly, one hour being represented by 0·6 inch and 0·09 inch respectively. Time marks are made twice daily on the water-level chart, so that it is generally possible to obtain the time at any point on the trace to within about ten minutes.

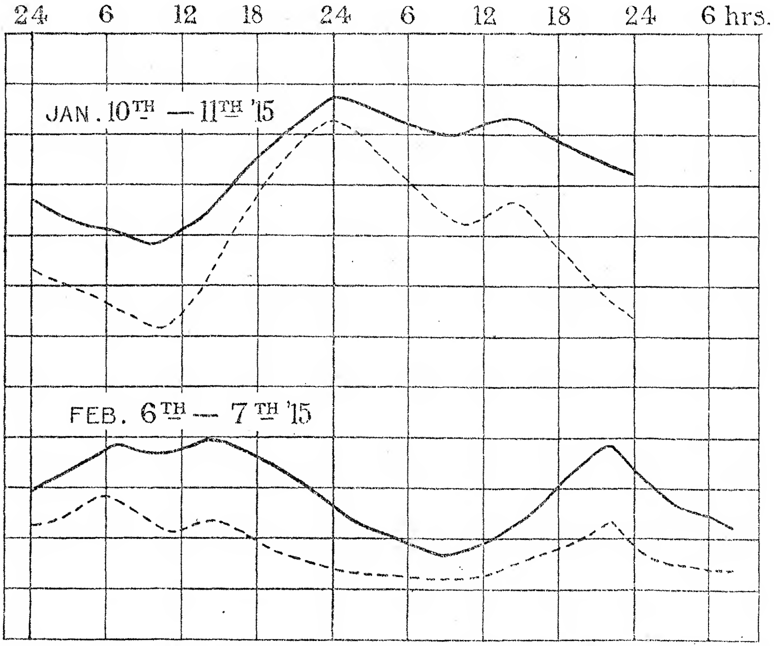

Fig. 3.—Broken line—water-level trace; full line—barograph trace inverted. Vertical divisions each represent 20 mm. in water-level and 12·7 mb. of pressure.

Judging from the two examples figured, it would appear that the pressure changes are very faithfully reproduced by the water-level recorder simultaneously with their occurrence. If there is any lag it must be a matter of minutes only. In order to verify this conclusion I have measured the times of occurrence of corresponding movements shown on the two traces in all cases that were suitable for the purpose during the year 1915. The chief qualifications for suitability were that the movement should be sufficiently outstanding to prevent any mistake in identifying it on the water-level trace, and that the feature to be measured—the barometric minimum during a depression for example—should be sufficiently abrupt to permit of accurate measurement of the time of its occurrence.

The results are given in Table V, and it will be seen that they show no systematic indication of lag in the water-level. Where times differ appreciably the difference is as often in one direction as in the other, and was undoubtedly due to some cause for uncertainty in the measurement. In most cases, however, the times agree within the limits of the errors of measurement.

Table V.—Times of Occurrence of Barometric Maxima, etc., and of Corresponding Water-Level Movements during 1915.

Date.	Character of movement shown on barograph.*	Time of occurrence, G.M.T.		$T_2 - T_1$.	Remarks.
		Barograph (T_1).	Water-level (T_2).		
		h. m.	h. m.	min.	
January 10...	Maximum	9 40	10 10	30	See fig. 3.
„ 10...	Minimum	24 0	24 0	0	„ „
„ 11...	Maximum	9 40(?)	10 0	20(?)	„ „
„ 11...	Minimum	14 40	14 20	−20	„ „
„ 16...	Minimum	2 26	2 30	4	
February 6...	Minimum	13 50	14 0	10	„ „
„ 7...	Maximum	8 50	8 50	0	„ „
„ 7...	Minimum	22 10	22 15	5	„ „
„ 9...	Minimum	7 15	7 10	−5	
„ 13...	Minimum	20 0	20 0	0	
March 6...	Minimum	15 50	14 30	−80	Minimum not well marked. Fairly steady from 14·30 to 15·50.
„ 18...	Sudden rise	19 4	19 0	−4	Squall.
„ 19...	Minimum	3 0	2 50	−10	
April 7...	Minimum	2 45	2 0	−45	Times agree if steady fall of water-level is allowed for.
„ 8...	Sudden rise	19 8	19 10	2	Squall.
December 25...	Minimum	12 15	13 0	45	Pressure nearly constant from 12 to 14 hours.
„ 26...	Maximum	20 5	20 15	10	

* The movement is inverted on the water-level trace.

It may be noted in passing that the data from which fig. 3 was drawn may be used to obtain values of $\delta u/\delta p$. Thus:—

January 10, 1915.—Mean level = 403 cm.; pressure range = 18·4 mb.; water-level range = 80·6 mm.; whence

$$\delta u/\delta p = -4{\cdot}38 \text{ mm./mb.}$$

February 7, 1915.—Mean level = 344 cm.; pressure range = 13·7 mb.; water-level range = 23·0 mm.; whence

$$\delta u/\delta p = -1{\cdot}68 \text{ mm./mb.}$$

These values would seem to be quite reliable and I have plotted them together with the data of Table III in order to obtain a curve, giving the variation of sensitiveness with water-level (fig. 4). The rapid increase of $\delta u/\delta p$ with rise of level is very striking.

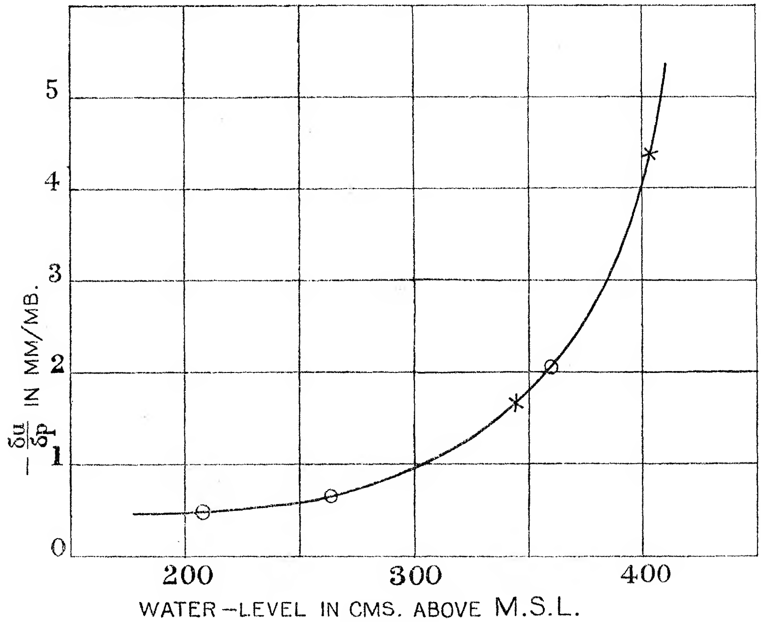

Fig. 4.

Returning to the question of lag, a further piece of evidence may be quoted in support of the conclusion arrived at. During times of high wind a broadening of the barograph trace occurs as a result of the phenomenon known as "pumping." The water-level traces are affected in a very similar manner. Now, if there were any lag in the response of the well, it is difficult to see how the rapid changes of pressure to which the movements are due could be registered. We may surmise that any sluggishness in the response to ordinary changes of pressure would be accompanied by insensitiveness to small and rapid movements. The records show, however, that the latter are recorded in a similar manner and apparently on the same scale as the former.

VII. *Summary of Results and Conclusion.*

We may summarise the results of the inquiry as follows:—

(1) At all seasons of the year the water-level is sensitive to changes of pressure, a rise of the barometer being associated with a fall of water-level and *vice versâ*.

(2) Within certain limits the change of level is proportional to the change of pressure producing it.

(3) The magnitude of the change of level produced by a given change of pressure increases rapidly as the subsoil water-level rises.

(4) There is no appreciable lag in the response of the water-level to changes of pressure.

These conclusions must be understood to refer to the level of the water in the well, because we have no justification for assuming that the effect of a change of pressure upon the free surface of water is the same as its effect upon the water held in the interstices of the soil. In fact, it is possible that the phenomena may depend upon a differential action of this nature.

The fact that barometric pressure is a factor of importance in relation to the movements of subsoil water appears to have been first recognised by Mr. Baldwin Latham.* His observations related chiefly to the Bourne flow in the Croydon district, and included soundings of deep wells. So far as can be ascertained from the brief notices of his two papers read before the British Association, his investigation of the response of the wells to pressure changes led to conclusions very similar to those enunciated above. We may suppose, then, that the phenomenon is a general one—probably with limitations imposed by the geological formation—exhibited by both deep and shallow wells. A further result obtained by Latham was that the rate at which percolation occurred increased with diminution of pressure. This conclusion he confirmed by direct observation with a percolation gauge, and attributed the phenomenon to the action of dissolved air and other gases in the water. He supposed that a diminution of pressure would result in the liberation of a certain amount of the gases, and that the consequent increased aëration of the soil would facilitate percolation. An increase of pressure would reduce percolation by causing an absorption of gases in the soil by the water.

The chief difficulty in applying Latham's theory to the Kew well appears to me to lie in the fact that there is no lag in the response of the well to changes of pressure. All the evidence which has accrued from the investigation of the movements of subsoil water at Kew indicates that percolation can only operate slowly in bringing about changes of level. Even during times of flood, when conditions are most favourable for rapid penetration, the water-level in the well continues to rise for hours after the surface water has begun to subside. It is therefore difficult to believe that any effect depending upon some change in the rate of percolation could follow so promptly upon the initiation of that change as we have found to be the case in the phenomenon under notice. There appears, therefore, to be a strong probability that the effects of pressure upon well-level are not secondary effects due to changes in the rate of percolation.

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* "On the Influence of Barometric Pressure on the Discharge of Water from Springs," 'B.A. Report,' 1881, p. 614; 1883, p. 495.

I have already indicated an alternative direction in which to look for an explanation of the observed results, namely, a differential action of pressure upon the free surface of water in the well and upon the subsoil water. The well behaves very much like the open arm of a manometer connected to a reservoir of air. If we suppose that the air contained in the interstices of the soil immediately above the water-line, or in cavities, is cut off from external pressure changes, the general character of the movements would seem to be sufficiently well accounted for. Any change of barometric pressure would result in a readjustment of the water-level in the soil and in the well, until uniformity of pressure at any given level below the water line was re-established. If this view is correct, it follows that the water-level in the well does not in general represent accurately the true subsoil water-level. The two levels would only coincide at some particular height of the barometer. It must also be supposed that any volumes of air concerned in the action are very perfectly cut off from external pressure changes, otherwise the well would behave like a micro-barograph, responding only to sudden changes of pressure. The results, however, point strongly to the conclusion that the rate at which the pressure is changing is of no consequence.

It would appear at first sight that this postulate is in opposition to the well-known phenomenon of the emission and absorption of gases by the soil in response to barometric changes. In deep mines this effect is of so great importance that special precautions may be necessary to prevent explosions under certain barometric conditions. In the case we are dealing with, however, the local circumstances are rather peculiar. The well is sunk through a concrete floor, is lined with glazed pipes, and is surrounded by a system of brickwork vaults. Under these circumstances it seems quite likely that cavities may occur containing imprisoned air in sufficient quantity to produce the observed results. The effects observed by Latham may also have been produced in some such way.

A third possibility is that the phenomenon may be the result of the distortion of the earth's crust and the water-plane under variations of pressure.

Sir G. H. Darwin* in 1882 showed that between two places on an otherwise flat earth of the rigidity of glass a difference of level of about 9 cm. would exist as the result of a difference of pressure equivalent to 5 cm. of mercury. Over the free ocean the water would be depressed 13·6 cm. for each centimetre of mercury increase of pressure. If the subterranean water plane were distorted to the same extent the depression per centimetre of mercury measured by an instrument on the surface would be 13·6 −1·8 cm. or 11·8 cm., which corresponds to a value of $a = -15·7$ mm./mb. The actual changes of level measured at Kew were considerably smaller than this, which implies either that the rigidity of the earth is much less than that assumed by Darwin or that the distortion of the subsoil water surface is a good deal less than over the free ocean. Darwin concluded that the elastic compression of the ground must take place without sensible delay, but it is at least doubtful whether the same statement is applicable to the subsoil water. Again, it is not easy to see why the observed effect should depend to so marked an extent upon the condition of the soil.

The above calculation may perhaps serve to give some rough idea of the order of magnitude of the effects which might be observed under certain circumstances, but the actual conditions are radically different from those postulated in Darwin's problem. The effects of various distributions of load upon the earth's surface have been worked out by Dr. C. Chree† and others in recent years, but so far as I know the solution for the case in which we have porous matter permeated with liquid up to a certain level is not yet available. It seems quite likely that the effects of elastic compression may be at least partially concerned in producing the results which I have detailed, and a mathematical treatment of the subject would be of great interest.

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* G. H. Darwin, "On the Mechanical Effects of Pressure on the Earth's Surface," 'B.A. Report,' 1882, p. 106.

† C. Chree, "Applications of Physics and Mathematics to Seismology," 'Phil. Mag.,' 1897, p. 173, *et seq.*